1. Title of the Project

Studying Spin-Transfer Torque in Epitaxial $La_{2/3}Sr_{1/3}MnO_3/SrTiO_3/La_{2/3}Sr_{1/3}MnO_3$ Nanopillars

2. Applicant

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4. Abstract

Nearly complete spin polarization of current in ferromagnetic oxide $La_{2/3}Sr_{1/3}MnO_3$ has been shown by different groups [1][2][3]. This unique property so far has not been taken advantage of in making spin-transfer torque devices, although, spin-transfer-driven magnetization switching [4][5] has been the subject of intensive study for many years now. However, introducing ferromagnetic oxides into this evolving field of knowledge is expected to open up new opportunities in today's spin-transfer torque science. Our aim is to make spin-transfer torque nanopillars using $La_{2/3}Sr_{1/3}MnO_3$ ferromagnetic oxide. Local studies on the effects of layer's thicknesses or temperature on magnetic domains will be carried out using Ballistic Electron Emission Microscopy. Furthermore, since spin-transfer ferromagnetic resonance technique has proven to be very effective in spin-transfer torque studies, we will employ this technique in order to investigate the magnetic damping as well as the roles of in-plane and out-of-plane torques in our devices.

5. Duration of the Project

4 years, starting from September 2010

6. Personnel

6.1 Senior-scientists

Name	Task in Project	Time
Dr. Tamalika Banerjee	Supervision and Supervision	30 %
Prof. Beatriz Noheda	Supervision	10 %
K. Gaurav Rana	PhD Student	10 %

6.2 Junior-scientists and technicians

Name	Task in Project	Time
Hiwa Modarresi	Experiments and Analysis	90 %
Johan Holstein	Technical Support	10 %
Bernard Wolfs	Technical Support	10 %

7. Cost Estimates

7.1 Personnel Positions

One ’onderzoeker in opleiding’ position for four years.

7.2 Running Budget

15 k€/year for conferences, summer schools and maintenance.

7.3 Equipment (k€)

Equipment	Costs
E8257D PSG Analog Signal Generator	~ 30
Stanford Research Systems SR830 DSP lock-in	~ 5

7.4 Other Support

This project is part of the larger research program of NWO-VIDI project Banerjee. Involved personnel described above are employed via Zernike Institute for Advanced Materials or associated research programs.

7.5 Budget Summary (in k€)

The expenses are summarized in the following table:

		2010	2011	2012	2013	2014	Total
position	PhD Student	25	50	50	50	25	200
	Postdocs	-	-	-	-	-	-
	Technicians	-	-	-	-	-	-
	Guests	-	-	-	-	-	-
Costs	Personnel	25	50	50	50	25	200
	Running Budget	5	15	15	15	10	60
	Equipment	5	35	-	-	-	40
Total		35	100	65	65	35	300

8. Research proposal

8.1 Introduction

The newly emerging field of Spintronics relies heavily on new materials that have magnetic properties. Gaining a deeper understanding of different ferromagnetic materials, and in particular their spin dynamics, is important for today's quickly evolving technology. Although, the birth of Spintronics can only be traced back to late 80s when giant magneto resistance (GMR) effect was first observed in magnetic multilayer systems, a great amount of work since then has been done in this area to further develop it.
Spintronics is based on the spin of electron, which is a fundamental property that originates from electron's spinning around its axis. Depending on the direction of the angular momentum that this spinning causes, electrons can have spin-up (when the angular momentum is pointed upward) or spin-down (when it is pointed downwards) states. GMR technology uses this unique property of electrons to detect a high or low current signal which later is respectively interpreted into one or zero digits to be used in data processing units. The first spacers, which were used as separators of top and bottom ferromagnetic layers, had a conducting nature however shortly after, thin insulating spacers were introduced in order to provide more spin injection. Utilizing this mechanism has led to the so called Tunneling Magneto Resistance (TMR) effect which is at least one order of magnitude more sensitive in translating the electron current into digital signal compared to GMR.
Figure 1.a shows the configuration by which we can see the GMR or TMR effect if the spacer between two ferromagnets is a metal or an insulator, respectively. Here the current is flowing in y-direction through the device. First ferromagnetic layer polarizes the electrons which are injected into the spacer. If the magnetization of second ferromagnetic layer is parallel to that of polarizer, electrons encounter minimum scattering from the interfaces while they are traversing through the stack. On the other hand, if the magnetization of second ferromagnetic layer is directed opposite to that of polarizer, electrons face a greater spin-dependent scattering. Considering the fact that this device can show a large or small resistance for anti-parallel or parallel orientations of the

magnetizations of ferromagnets, respectively, it can work as a valve and that is why this device is sometimes called Spin Valve.

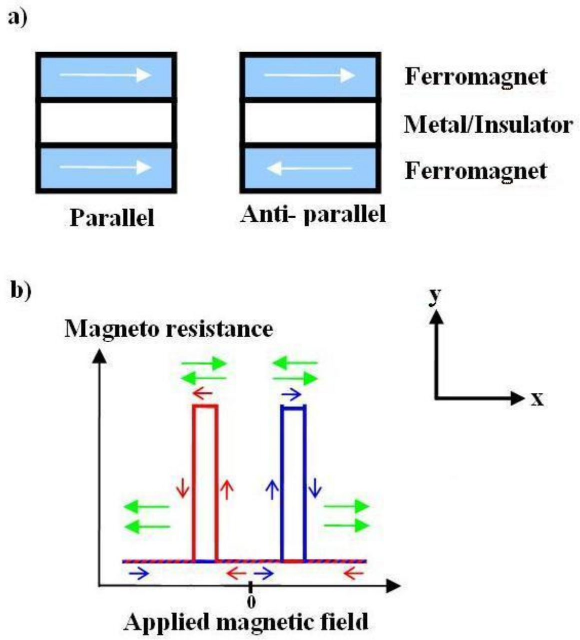

Figure 1 a) Device configuration of either GMR or TMR when the spacer is a metal or an insulator, respectively. b) A simplified picture showing the TMR ratio versus external magnetic field.

In both giant magneto resistance and tunneling magneto resistance configurations, one ferromagnetic layer is usually made more susceptible to the external applied magnetic field via different ferromagnetic materials or through shape anisotropy. This allows us to control magnetization directions of different ferromagnetic layers with the external magnetic field. Figure 1.b shows a simplified representation of dependence of magneto resistance on external applied magnetic field. In the left-hand side of this figure, magnetization directions of both ferromagnets are pointed to the left and therefore resistance of the device shows a minimum. We follow the blue arrows by decreasing the magnetic field down to zero, then switch the direction of the applied magnetic field and increase it until we change the magnetization direction of one of the ferromagnetic layers. At this moment we see a huge resistance in the device. By further increasing the external magnetic field we change the magnetization direction of the other ferromagnetic layer and we again see a small resistance in the device. We can repeat the same kind of experiment by following the red arrows from the far right in figure 1.b, i.e. by reducing and then reversing the direction of applied magnetic field. Doing this we would get a mirror like image of what we got by following blue arrows. While studying magnetic junctions, TMR (or its equivalent GMR) ratio is a measure that is used to show the effectiveness of the spin valve. This ratio is defined as:

$$TMR = \frac{R_{AP} - R_P}{R_P} \qquad (1)$$

Here R_{AP} (R_P) is the resistance of the ferromagnetic multilayer when the magnetization directions of the ferromagnets are anti-parallel (parallel).

In a normal metal the number of spin-up and spin-down states are the same. However, in a ferromagnet it is not. As it is shown in figure 2, at Fermi level, the number spin-up states in more than spin-down states.

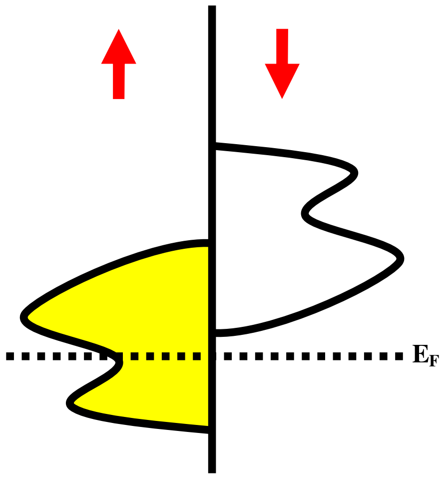

Figure 2 spin-up and spin-down states around Fermi level. Only spin-up states are occupied by the electrons at Fermi energy.

If spin polarization in a ferromagnetic layer is defined as:

$$P = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} \quad (2)$$

Where N↑ (N↓) is the number of density of states at Fermi energy for spin-up (spin-down) electrons, using the TMR ratio one can show:

$$TMR = \frac{P_1 P_2}{1 - P_1 P_2} \quad (3)$$

This relation is called Julliere equation which is of great significance since it relates the TMR ratio to the spin polarization of the two ferromagnetic layers. In this relation P_1 and P_2 show the polarization of top and bottom ferromagnetic layers.

8.2 Spin-Transfer Torque

Spin-transfer torque is a phenomenon in which magnetization direction of a thin ferromagnetic layer is reoriented using a spin-polarized current. In fact, at very small device scales a spin-polarized current can transfer its spin angular momentum to a small magnetic element. A spin polarized [6] current is one with more electrons of either spin up or down and can be produced by passing a current through a magnetic layer. Spin-transfer torque technology has a promising potential in magnetic random access memory (MRAM) devices. However, the amount of current needed to reorient the magnetization, called the critical current, at present is too high for commercial applications, and the reduction of this current density is one of the aspects of current academic research in

Spintronics. Current density in a spin-transfer torque element can be derived from Landau-Lifshitz-Gilbert (LLG) equation (LLG equation will be discussed later in this proposal) as follows [4]:

$$J_C = \frac{2e}{h}\frac{\alpha Mt}{g(P,\mu)}B_{eff} \tag{4}$$

In this relation e is electron charge, h is plank's constant, α is the Gilbert's damping parameter, M is the saturation magnetization of the switching layer, B_{eff} is the effective magnetic field acting on switching layer, t is the thickness of spin torque element, and $g(P,\mu)$ is spin torque efficiency function. Existing industrial demands, for commercial feasibility of the spin-transfer torque switching, would require switching current densities of less than 10^5-10^6 A/cm^2 [4].

The first prediction and experimental verification of spin-torque-driven magnetization dynamics dates back to the work of Berger in 70s. He predicted current-driven domain wall movements [7] and later provided the experimental proof [8]. However, the 45 amperes current which he used to drive the domain walls within thin films proved the device to be impractical for industrial applications. The greatest impetus for the commencement of research on the current effects on the magnetization dynamics was provided by a theoretical work of Slonczewski [9] and, independently, by Berger [10] this time on nanostructured ferromagnetic thin films. Their original argumentation was quite general; as angular momentum is conserved in a system containing itinerant electrons and local magnetic moments, every divergence of a spin-polarized current (spin current) of itinerant electrons will be accompanied by an opposite and equal change of angular momentum of the local moments (spin torque) [4].

From theoretical point of view many works has been done to describe the interaction between spin current and spin torque. One of the basic equations describing this interaction is LLG equation that is a differential equation used for describing the precessional motion of magnetization in a magnet. However, by itself this equation is unable to explain the physical aspects of nano-structured magnetic structures. Zhang *et. al.* [11] developed the LLG equation, for spin-transfer torque purposes, via adding a new term to it. The modified equation is written as:

$$\frac{d\vec{M}^{1}}{dt} = -\gamma_0 \vec{M}^{1} \times \vec{H}_e - \gamma_0 b \vec{M}^{1} \times \vec{M}^{2} - \gamma_0 a \vec{M}^{1} \times (\vec{M}^{2} \times \vec{M}^{1}) + \alpha \vec{M}^{1} \times \frac{d\vec{M}^{1}}{dt} \tag{5}$$

In which $\vec{M}^{1}$ and $\vec{M}^{2}$ are magnetization vectors of switching and pinned layers respectively, while $\vec{H}_e$ represents the overall magnetic field (including the contributions from the magnetization layers and external field). γ_0 is a constant called the gyromagnetic ratio, but α is called Gilbert's damping parameter and has to be calculated in spin-transfer torque experiments as it will be discussed later. The first and the last terms in equation (5) contribute to the LLG damping, while the middle ones are modifications introduced by Zhang *et. al.* and are the terms responsible for magnetic moment switching.

The second term in this equation accounts for the torque due to effective field from $\vec{M}^2$ and the third one is representing spin torque in the modified LLG equation. Constants *a* and *b* in equation (5) can be calculated using the following equations:

$$a = -\frac{hj_e a_0^3}{\sqrt{2}e\mu_b\lambda_J}\left(\frac{1-\cos\xi\ e^{\xi}}{\xi}\right) \tag{6}$$

$$b = -\frac{hj_e a_0^3}{\sqrt{2}e\mu_b\lambda_J}\left(\frac{\sin\xi\ e^{\xi}}{\xi}\right) \tag{7}$$

$$\xi = t_F / (\sqrt{2}\lambda_J) \tag{8}$$

In which λ_J is the transverse spin decaying length, *h* is plank's constant, *e* is electron charge, μ_B is the magnetic permeability, j_e is the electric current, a_0 is the lattice constant, and t_F is the thickness of the switching layer.

At this point it is worth explaining, in a simplified way, how a spin-torque-driven magnetization works. Figure 3 schematically shows a pillar stack of a spin-transfer torque element. This spin-transfer torque element, from bottom to top, consists of pinned polarizing layer, spacer layer, and switching (sometimes called free or analyzing) layer. Polarizer and switching layer consist of ferromagnetic materials. The polarizing layer provides a magnetization of M_P that remains fixed in space (here in x-direction), while the switching layer's magnetization, M_S, is easy to rotate. Imagine a current comprising of both spin-up and spin-down electrons is injected into this pillar stack from the bottom in z-direction. At polarizing layer the majority spins (shown as white arrows) are transmitted and the minority spins are reflected or transformed into majority spins via spin flip scattering process within the polarizing ferromagnetic layer. In their next stage, this spin-polarized current is injected into a non-magnetic spacer layer. Spacer layer, in fact, decouples the polarizer from the switching layer and it has to be thin enough to retain the spin polarization direction of electrons passing through it.

A prerequisite for spin-torque driven magnetization to happen is that there should be a non-zero angle ($\theta \neq 0$) between the magnetization directions of polarizing and switching layers as it is shown in figure 3. In this case the spin-polarized current exhibits a transverse component relative to the magnetization of the switching layer. Due to the large energy contribution of the transverse spin component with respect to the exchange interaction, it is strongly absorbed within the interface region. It is this absorption of the transverse spin current that results in a spin-torque reorienting the magnetization direction of switching layer parallel to that of polarizing layer (i.e. x-direction) [4].

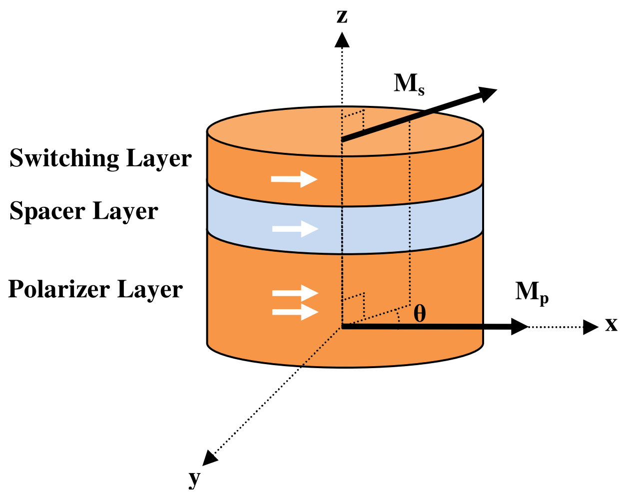

Figure 3 Schematic representation of a spin-transfer torque element. Magnetization directions of pinned and switching ferromagnetic layers are on parallel planes but there is θ angle difference between them.

If the direction of the electron current within this pillar element is reversed (i.e. if the injected electrons are entering the pillar stack from switching layer), the direction of the spin-torque also becomes reversed (the torque tries to align the magnetization direction of switching layer anti-parallel to that of polarizer, i.e. in the negative-x-direction). In this case, by flowing through the switching layer the current becomes spin polarized, the current which is passing through the spacer is thus polarized. At the interface to the polarizing layer, however, the direction of the magnetization differs with respect to the spin polarization (as the directions of the magnetizations of polarizer and switching layer were assumed to be different). The new quantization direction finally leads to electrons which are polarized anti-parallel to the polarizer's magnetization and those which are polarized parallel. While the first are reflected to the switching layer or partly reversed by spin-flip scattering within the polarizer, the latter are transmitted through the polarizing layer. In this geometry, the electrons backscattered from the interface of the polarizer are responsible for the spin-torque-driven magnetization switching which implies that because of more loss in the spin current, this spin-torque effect would be weaker in magnitude [4].
The dominant bias-dependent (at least for the small bias) component of the torque is the one in the plane of the switching layer, $\tau_{//}$. However, it is more convenient to consider the derivative of the torque with respect to bias, $d\tau_{//}/dV$, which has been given the name "parallel torkance" [12], in analogy to the differential conductance, dI/dV. When the spin-torque is roughly proportional to V, the torkance is roughly constant and its magnitude conveys the effectiveness with which a bias generates the torque [5]. The other component of the torque is the one perpendicular to the plane of the switching layer, $\tau_{\perp}$, or its derivative with respect to bias, $d\tau_{\perp}/dV$, which in this case is called "perpendicular torkance". Although this component is much weaker than the parallel torkance [5], it should be always taken into account while explaining any precessional behavior of the magnetization direction of the switching layer. Figure 4 and the discussion that follows show that the torkance is especially useful when Spin-Transfer Ferro-Magnetic Resonance (ST-FMR) [13] technique is employed to study the spin-torque effect with high accuracy.

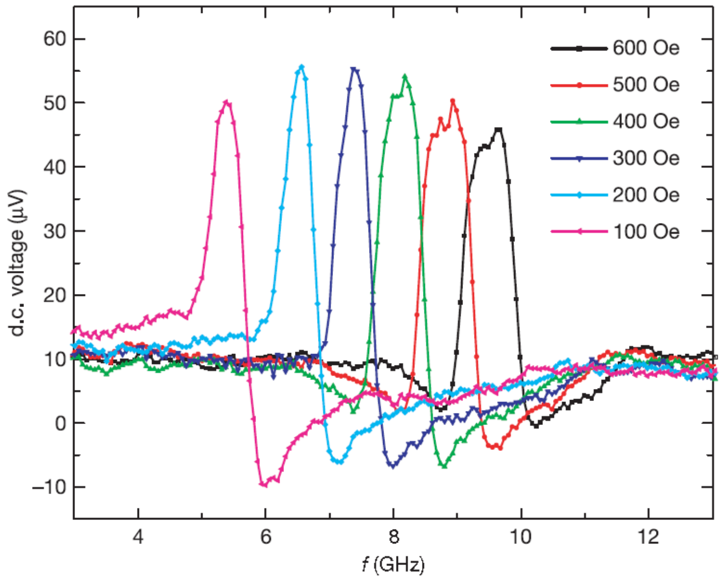

Figure 4 DC-voltage peaks in different external magnetic fields as a response to the traversing AC-current. The DC-voltage results from the resonant oscillation of the magnetic moment of the switching layer by current-induced spin-transfer [14].

In figure 4, DC-voltage is plotted as a function of the frequency of the injected AC-current which in this case was *0.55 mA*. External applied magnetic fields are also shown mentioned on this picture. The DC-voltage results from the resonant oscillation of the magnetic moment of the switching layer because of the current-induced spin-transfer [14]. ST-FMR provides a means to measure the perpendicular and parallel torkances simply from DC-voltage graph versus injected-current frequency. Once the conductance (*dI/dV*) is known, parallel torkance can be calculated using the following equation [13]:

$$\frac{d\tau_{II}/dV}{\sin\theta} = \frac{\pi h}{2e}\frac{2P}{1+P^2}\left(\frac{dI}{dV}\right) \tag{9}$$

In this equation, P is the polarization of the switching layer and θ is the angle between magnetization directions of pinned and switching layers. At the same time it is possible to measure the effective damping coefficient of switching layer, α_{eff} , from the plot shown in figure 4 via following equation:

$$\alpha_{eff} = \frac{2\sigma}{\omega_m(\Omega_\perp + \Omega_\perp^{-1})} \tag{10}$$

In which,

$$\sigma = \frac{\alpha\omega_m}{2}(\Omega_\perp + \Omega_\perp^{-1}) - \cot(\theta)\frac{\gamma\tau_{II}(V,\theta)}{2M_s} \tag{11}$$

$$\Omega_\perp = \gamma(4\pi M_{eff} + H)/\omega_m \tag{12}$$

Where ω_m is the resonant precession frequency, α is the Gilbert damping coefficient, M_{eff} is the effective magnetic anisotropy, and M_s is total magnetic moment of the switching layer.

8.3 Ferromagnetic oxides

Concomitant with the development of metal-/semiconductor-based Spintronics since the late 1980s, important advances have been made regarding ferromagnetic oxide thin films and their applications in Spintronics. The first notable record of using magnetic oxides as electrodes in magnetic tunnel junctions yielded tunnel magneto-resistance ratios that were one order of magnitude larger [15] than what had been obtained from transition-metal electrodes. Later it was found that some of ferromagnetic oxides can act as half metals. A half metal only has one of spin-up or spin-down electron states in its Fermi level and therefore has a conductive nature for electrons having the spins of available states and insulating nature for the electrons having the other spin orientation, as it is shown in figure 2. It is indeed very straightforward from the Julliere formula (equation (3)) that materials having high values of spin polarization would yield high TMR values.
A remarkable impact on the ferromagnetic oxide Spintronics came with the prediction of nearly 100% spin polarization (half metallic) in $La_{2/3}A_{1/3}MnO_3$ (with A being either of the Ca, Sr, or Ba atoms) [16]. Notable evidences following this theoretical prediction came with the direct experimental demonstration of half metallic nature of $La_{2/3}Sr_{1/3}MnO_3$ (LSMO) [2]. Further boosting this idea was the 1800% TMR-ratio demonstration of $La_{2/3}Sr_{1/3}MnO_3/SrTiO_3/La_{2/3}Sr_{1/3}MnO_3$ magnetic tunnel junctions at 4 K [1]. From this TMR value a spin polarization of at least 95% is inferred, which strongly underscores the half-metallic nature of LSMO. Nevertheless, detailed experimental results suggest that LSMO does have minority spin states at its Fermi level but since the current from majority spin-states is much higher than that of the minority spin-states [3], this material can mimic the behavior of a true half-metal in transport experiments.

8.4 Device Fabrication

As it is implicitly inferable from the aforementioned text, our aim in this project is to fabricate and investigate spin-transfer torque devices which are made using LSMO ferromagnetic oxides as their pinned and switching ferromagnetic layers. One of the ferromagnetic layers can be pinned using shape anisotropy, i.e. via being thicker than the switching layer as it is shown in figure 3. In such epitaxial spin-transfer torque devices, transmission is expected to be larger in comparison to metallic counterparts.
Magnetic tunnel elements are of importance concerning nonvolatile memory applications due to their high tunnel magneto-resistance values at room temperature [4]. Electrons flow through the tunneling layer would provide a high spin polarized current injected into the switching layer. Therefore having a thin (e.g. few nanometers) decoupling tunnel barrier in between pinned and switching ferromagnetic layers, that retains the spin polarization direction of electrons, is an essential part of this research. Here we have chosen this barrier to be $SrTiO_3$ (STO). The most important reason to choose STO as the barrier is that it has a very good lattice match to that of the LSMO lattice. Furthermore, STO has a thermal expansion coefficient ($\sim 11\times10^{-6}$ K^{-1}) that is very close to that of LSMO ($\sim 11.5\times10^{-6}$ K^{-1}) which guarantees a crystal misfit of less than 1% [17] for all temperatures below 1000 K.

In order to grow thin epitaxial layers of LSMO or STO with high precision, the best option is to use Pulsed Laser Deposition (PLD) technique. It has been shown that single crystalline epitaxial layers of LSMO and STO [18] can be deposited using this technique. Moreover, in PLD, layer by layer deposition can be achieved using Reflection High Energy Electron Diffraction (RHEED) technique.
The substrate choice in this project is of great significance and one should note the importance of both lattice parameters and conduction properties of the substrate. To ensure the best lattice match between the deposited layers and substrate, the indispensable option is single crystalline STO (100) substrates. The next criterion in choosing the substrate reflects the importance of the conductive nature of the substrate. Substrate must be conducting since the magnetic properties of the deposited ferromagnetic oxides are to be studied using Ballistic Electron Emission Microscopy and ST-FMR. STO is a very good insulator by itself and to turn it into an n-type semiconductor it must be doped with Niobium. Various weight percents of niobium atoms doped into the STO (NbSTO) are already available in the market.
For different reasons from leakage problems to the single domain formation in deposited ferromagnetic layers, active areas in our devices must be made in different dimensions. This will give us the opportunity to better study the leakage, power consumption, stability of the magnetization direction, and other potential topics that may rise during the studies. Based on what already has been done in spin-transfer torque elements, we know that active areas of the devices must be in the order of 100x200 nm^2 [5]. Each substrate will have a dimension of 6.6x6.6 mm^2 (this limitation is imposed by the sample holder size inside the BEEM system) and the final patterns of active area are made on these samples using Electron Beam Lithography (EBL) technique. The elongated shape of the active area gives the deposited magnetic layer a preferred magnetic anisotropy so that it tends to align along this easy axis direction. Figure 5 shows a simplified geometric representation of our spin-transfer torque device. Here, SiO_2 insulating layer limits the passage of the current only to the active area and ideally eliminates the leakage current. The bottom LSMO ferromagnetic layer is pinned while the top LSMO layer can be switched. In between these two thin (i.e. a few nanometers) layers, STO sits as the tunnel barrier. While SiO_2 layer will be deposited using a sputtering machine, all different stacks of spin-transfer torque element (i.e. LSMO/ST/LSMO) will be in situ deposited using PLD technique.

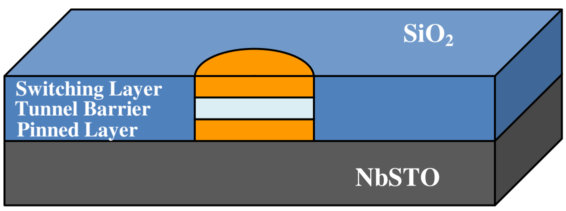

Figure 5 schematic representation of the proposed device. Two LSMO ferromagnetic layers have STO tunnel barrier sandwiched in between. In this representation the top LSMO layer is switchable while the bottom LSMO layer is pinned.

8.5 Measurement techniques

Ballistic Electron Emission Microscopy (BEEM) provides a very strong and unique opportunity to study the behavior of bulk magnetic domains and their walls with changing temperature or external magnetic field. It has proved to be very effective in studying ferromagnetic tunnel junctions [19]. Apart from this unique characteristic it can also perform detailed transmission measurements, spectroscopy studies, and surface topography. All these unique characteristics are clearly seen in different published works including ballistic hole magnetic microscopy studies done by my main PhD supervisor [20]. It is worth mentioning that I have helped in low temperature installation of BEEM system in my master project.

Another key element in characterizations needed to perform this project is Spin-Transfer driven Ferro-Magnetic Resonance (ST-FMR) [14] technique. ST-FMR has provided a means for quantitative and qualitative measurements of the magnitude and direction of the spin-transfer torque as well as magnetic damping characterization of switching layer (or its possible coupling to the pinned ferromagnetic layer) in ferromagnetic tunnel junctions. In ST-FMR experiments, the initial orientations of pinned and switching ferromagnetic layers are offset by an exchange bias, an applied magnetic field, or both. Then a microwave-frequency (i.e. several gigahertzes) current is used to apply an oscillating spin current into the pillar structure. When the applied frequency matches the resonance frequency of one of the magnetic normal modes, the resulting precession causes the resistance of the pillar stack to oscillate at the same frequency as the applied spin current. This is especially useful when one tries to bolster a single mode of vibration and diminish the other vibration modes. Since the thresholds for spin-torque driven excitations are determined by a competition between the spin torque and magnetic damping, the frequency line width of this resonance provides a measure of the magnetic damping. Also, this lineshape as a function of frequency gives a measure to determine the magnitude and direction of the bias dependent part of the spin torque [14]. If only an in-plane component of the torkance is present, the frequency lineshape is predicted to be a simple Lorentzian [5] that is symmetric around the center of the resonance. If in addition (or instead) there is a non-zero perpendicular component of the torkance, the frequency lineshape would be an anti-symmetric lorentzian [5]. By fitting a model to these symmetric and anti-symmetric resonance shapes, their amplitudes and consequently in-plane and perpendicular components of the torkance are easily obtained [5]. An explanation regarding parallel and perpendicular torkance is already given in the discussions related to figure 4.

8.6 Goal of the Proposal

Since so far no work has been done on studying spin-transfer torque properties of epitaxially grown LSMO/STO/LSMO nanopillar stacks, there is ample scope for research in this field. These research directions will benefit from studies currently ongoing with metal systems. Although we know much of today’s research in spin-transfer torque is aimed at decreasing the critical current in tunnel junctions and increasing the reliability of the junctions, our goals are more to investigate and enrich the basics of this field using ferromagnetic oxide materials. On this basis, the following outline is foreseen for the duration of this PhD project and we hope it directly or indirectly facilitates the realization of those goals.

✓ **local study of magnetic domains**

BEEM technique will be used to study the effects of temperature (down to liquid helium temperature) and external magnetic field on the behavior of magnetic domains and their walls [20]. Initially these experiments will be carried out on LSMO/NbSTO devices and then once the full pillar stack is fabricated, the same experiments will be performed on the whole stack. Furthermore, we will study the differences in critical current density [21] across different regions of the pillar stack and differences in the local magnetization behavior.

✓ **The angular dependence of spin transfer torque**

We will investigate the sinusoidal dependence [22] of the spin-transfer torque on initial angle between the magnetization directions of the pinned and switching magnetic layers. This dependence may provide a means for the better understanding of different mechanisms that are involved in magnetic damping.

✓ **The barrier-thickness dependence of spin-transfer torque**

Since experimentally or theoretically the dependence of spin-transfer torque and hot electron injection on barrier thickness is not known [5] in oxide tunnel junctions, oxide barrier thickness variation will make an interesting part of our research. This investigation is also partly of interest since the spin torque exerted on the switching layer will be strongly affected by inhomogeneities. In line with this, we tend to study different properties of our spin-transfer torque devices for different thicknesses of switching and pinned ferromagnetic layers.

✓ **Magnetic damping studies**

Magnetic damping in our devices will be mainly studied using ST-FMR technique as it has been explained in the measurement techniques section. It will be also interesting to see if it is possible to investigate the energy flow from the more-uniform fundamental mode of vibration to other weaker vibration modes due to their non-linear coupling as this is likely one of the fundamental mechanisms giving magnetic damping [5]. This effect will probably depend strongly on the thickness and area of our devices as well, something which needs to be investigated.

✓ **Temperature dependence of spin-transfer torque**

Knowing that tunnel junctions, because of their high resistance, produce more ohmic heating, this heating may be harnessed to quickly decrease the total magnetic moment in a switching layer [5]. This may result in less spin current needed to change the magnetization direction of the switching layer. Studying the effectiveness of harnessing heat to reverse the magnetic layer in a more efficient way (i.e. faster and/or using less spin current) may be another interesting topic in our research.

Finally if the abovementioned targets are investigated and time still permits, we can start the following works:

- ✓ Modifying the existing macro-spin models so that they can better explain both the interface spin asymmetry coefficient parameters [23] and normal or inverse state (known by that time) of the spin-transfer torque in ferromagnetic oxides.

- ✓ Replacing the insulating element in the ferromagnet/insulator/ferromagnet spin-transfer torque device by a metal. In our research this can be done by replacing the STO barrier with metallic oxide $SrRuO_3$ [24] that has proved to have a good lattice match with that of LSMO.

8.7 Collaborations

The main collaboration in this project will be with the group of Beatriz Noheda. In this collaboration epitaxial layers will be deposited using their PLD system. Furthermore, if needed, other experimental characterizations may take place in their group. This may include Superconducting Quantum Interface Devises (SQUID), low temperature four probe station setup, and etcetera. We will make other collaborations with other groups inside the Zernike institute. These collaborations are required for High Resolution Transmission Electron Microscopy (HR-TEM) studies of our samples. HR-TEM images will be taken in collaboration with Bart Kooi's group, while surface studies will be carried out mainly in collaboration with Petra Rudolf's group.

8.8 Plan of Work

The plan of work is summarized in the following table:

Time (months)	**Activity**
0-6	Optimizing the LSMO growth on NbSTO
6-24	Optimizing the steps involved in making the full nanopillar stack
24-36	BEEM Studies on magnetic domains and transmission of nanopillars
36-45	ST-FMR installation; Measurements and analysis of nanopillars
45-48	Thesis writing

Of course, deviations from this scheme might occur depending on the problems or interesting new physics encountered.

9. Infrastructure

In my master I have gained knowledge of making devices using ferromagnetic oxide materials in general and LSMO/NbSTO in particular. All different procedures and discussions needed in order to get to the point in which an epitaxially grown LSMO/NbSTO diode is made, has been mentioned in my master thesis. There is also an ample infrastructure in order to perform the proposed project in the Zernike Institute for Advanced Materials. I have already mentioned some of the available equipment in the Collaborations' section. Furthermore, in our own group, Physics of Nanodevices, there is a good infrastructure to manufacture and characterize our devices. For example, the BEEM system which is one of the integral parts of this research program is owned by this group. In addition, our clean room is equipped with EB/UV lithography and sputtering machines, which will be needed during our device fabrication process.

10. Application perspective in industry, other disciplines or society

The experimental realization of a commercial spin-transfer torque device will be a big step forward in the field of magnetic memories. The idea of making spin-transfer torque based devices are in line with the greater dreams of various industrial corporations for different reasons. First, it may give an opportunity to reduce the size of each storage bit. Second, it may provide faster switching speeds that result in faster data processing. And third, it may result in MRAM devices that have lower energy consumption than today's MRAMs which also means less heat generation inside the memory storage units. Realization of these ideal goals depends on the collective work of different researchers in various parts of the world. For our research project, even if the expected experimental realization has not been achieved at the end, much fundamental information has been gained in this field that can pave the way for other researchers to move towards those goals.

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